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Compositionally graded Ti6Al4V + TiC made by direct laser fabrication using powder and wire

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Abstract

Ti6Al4V reinforced with TiC has been fabricated as compositionally graded material by direct laser fabrication using TiC powder and Ti6Al4V wire which were fed simultaneously into the laser focal point. The microstructure along the length of the sample has been characterised using X-ray diffraction and scanning electron microscopy. The results show that the composition along the length changes as expected from the imposed changes in feed rate when allowance is made for the different capture efficiency for the powder and the wire. Some unmelted TiC has been observed in regions where the TiC fraction was high, but along most of the length of the samples TiC was completely melted and formed primary TiC, eutectic TiC and secondary TiC. Some preliminary tribological properties of the compositionally graded material were obtained using a sliding wear test which showed that the tribological properties of Ti6Al4V are improved by the reinforced TiC particles with the optimum frictional behaviour being found with approximately 24 vol% of TiC.

Keywords: Direct laser fabrication; Functionally graded materials; TiC-reinforced titanium alloys

1. Introduction

In the last few decades, metal matrix composites (MMCs) have been widely studied by metallurgists and a number of manufacturing techniques have been developed for their production. A large amount of work has focused on TiC- or TiB-reinforced, Al, and Mg and Ti composites because of their low density, high strength to weight ratio, and in the case of Ti and Al their corrosion and oxidation resistance. The ductilities of these composites are invariably very low and it is difficult to assess any trend in properties as a function of TiC content from tensile tests. For this reason, the tribological properties have been used to assess the change in properties over a range of compositions. Comparison will also be made with other methods of improving wear resistance which is notoriously bad in Ti alloys.

Various surface modification process have been carried out to improve the hardness and the wear resistance of those alloy, such as physical vapour deposition, chemical vapour deposition, ion implantation with nitrogen and plasma ion nitriding, laser cladding, common casting technique and thermal oxidation [1–10]. Although some of these processes have been very successful in improving the wear properties the coatings are somewhat thin to provide protection under severe wear conditions. The samples produced by direct laser fabrication (DLF) which retain any improvement in wear resistance throughout their thickness, may offer an alternative approach to improving wear resistance and it is thus a useful approach to assess the success of the manufacture of the TiC-containing samples via their wear resistance.

The technique of DLF is a net shape technology which incorporates features from stereolithography and laser surfacing, using computer-aided design file cross-sections to control the forming process. Powder-metal particles are delivered in a gas stream into the focus of

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a laser to form a molten pool. The part is then driven on an x–y stage to generate a three-dimensional part layer by layer.

The aim of the present study is to use this technology to manufacture a range of composite samples with different fractions of TiC by feeding TiC and Ti6Al4V simultaneously into the laser. The wear properties will be used as a first filter to assess the samples with different fractions of TiC. However, the low capture rate of the powder (10–30%) is a big problem of this technology, leading to wastage of the powder if two powders are used as feedstock. In order to overcome this problem, Ti6Al4V wire has been used as one feedstock and TiC powder as the other. These were fed simultaneously into the laser. In this preliminary study, this approach has been used to create compositionally graded materials in order to identify the optimum composition in terms of wear resistance.

Fig. 1 shows the schematic of the DLF facility used in this study for the manufacture of compositionally graded Ti alloys using simultaneous powder and wire feed. The fabrication is carried out in an atmosphere-controlled glove box with the oxygen kept below 5 ppm. During the process, the powder feed rate and the wire feed rate are controlled separately so that functionally graded samples can be manufactured by gradually increasing the powder feed rate and/or decreasing the wire feed rate.

This study has focused on optimising the processing condition and assessing the microstructure in terms of the wear properties of the compositionally/functionally graded samples.

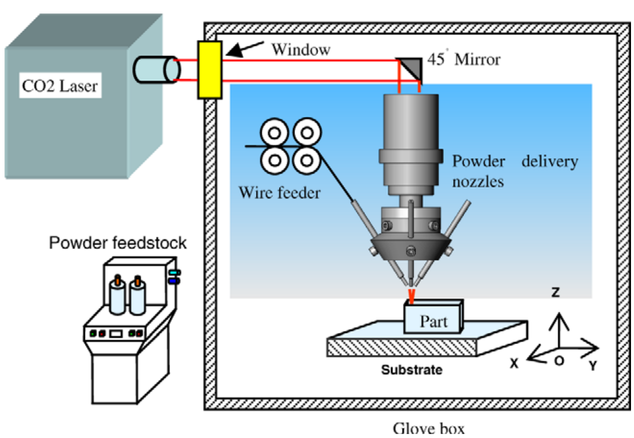

Fig. 1. Schematic of direct laser fabrication facility with simultaneous powder and wire feed.

2. Experimental procedures

The materials used in this work are Ti6Al4V (wt%) wire with a diameter of 0.45 mm and a TiC powder (>99.5% purity) with particle size ranging from 100 to 200 μm. Fig. 2 shows the structure of the TiC powders. Each particle is an agglomerate of very fine TiC particles (2–10 μm) as shown in the Fig. 2b. A hot rolled Ti6Al4V plate of 20 mm thick was used as substrate, which was ground with 320 grit SiC paper, and then degreased with acetone and ethanol before being used.

A ROFIN SINAR TRIAGON 1750W CO_2 laser was used which was operated at 1148 W CW laser, with a 12.5 cm lens, +37 mm defocus, and 150 mm/min scan speed. A computer numerical control (CNC)-controlled wire feed system, using a precision wire feed nozzle developed in-house, was used which can deliver wires with a diameter $\geqslant$0.4 mm. A TWIN 10-COMPACT powder feeder system, which was modified so that the powder feed speed could be accurately controlled by the CNC system, was used to deliver the TiC powder. The FGM samples which were produced were 5 mm × 25 mm × 45 mm.

A Leica light optical microscope with Zeiss KS 300 software was used for measurement of the volume fraction of the TiC. A JEOL 7000F scanning electron microscope coupled with an Oxford X-ray energy dispersive X-ray (EDX) system was used for microstructural analysis. A PHILIPS Xpert diffractometer, with Cu Kα radiation was used to obtain diffraction data.

The wear properties were assessed using a pin-on-disc machine tribometer. During pin-on-disc experiments, samples with or without TiC reinforcement were rotated against a stationary hardened bearing steel ball of 8 mm diameter at a speed of 66 rpm (0.031 m/s). The nominal diameter of the wear track was 9 mm and the normal contact load was 10 N. The sliding distance was 250 m and tests were conducted in air and without lubrication.

Wear was determined by measuring the cross-section of a wear track with a stylus profilometer. While the stylus was moving across the wear track, the vertical and horizontal positions of the stylus were recorded and later processed by Microsoft Excel so that a 2D profile of the wear track was obtained. Wear volume loss was obtained by integrating the area across the wear scar profile, and multiplying by the circumferential length of the track. Three measurements were performed for each track and average values are reported.

For the first 5 mm of a build only Ti6Al4V wire was fed to the laser molten pool. At each 5 mm increment the powder feed rate was changed automatically by the CNC program according to the scheme illustrated

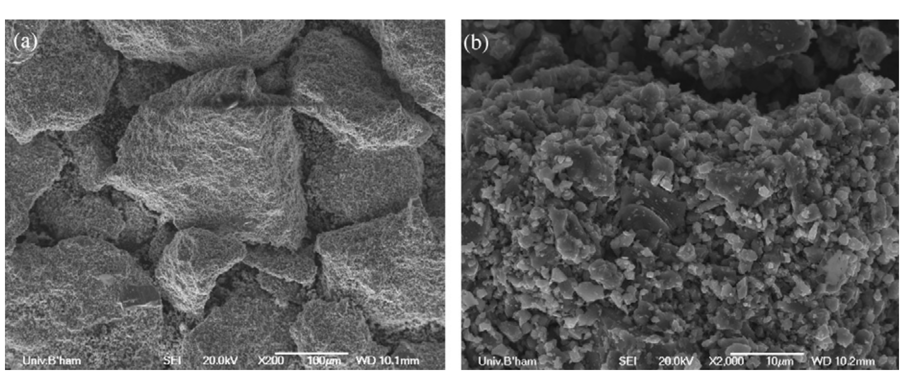

Fig. 2. Secondary electron scanning micrographs of TiC powder: (a) the macrostructure of the TiC powders and (b) the microstructure of a single TiC particle shows that it is an agglomerate of very fine TiC particles (2–10 μm).

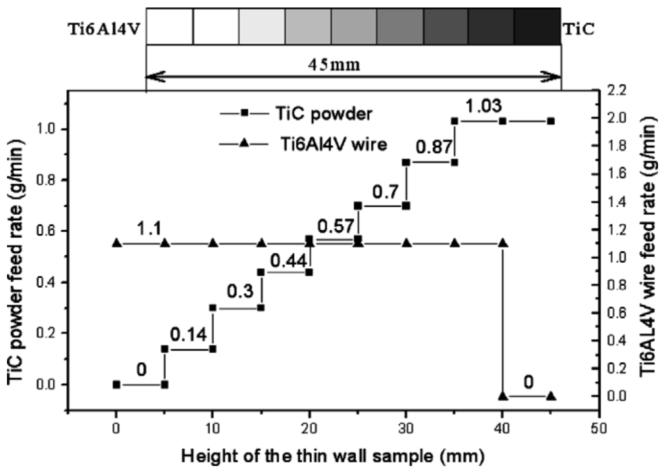

Fig. 3. A schematic of TiC powder and Ti64 wire feed rate used for the fabrication of the compositionally graded sample.

in Fig. 3. At the same time, the wire feed rate was maintained at 1.1 g/min until the sample reached a height of 40 m after which only TiC powder was delivered for the last 5 mm. The samples were cut, mounted, ground, polished and etched, for optical and SEM examinations.

3. Results and discussion

3.1. Scanning electron microscopy

Fig. 4 shows the typical microstructure of TiC-reinforced compositionally graded sample. In Fig. 4a, corresponding to 100% Ti6Al4V, the microstructure consists of coarse α laths of different orientations with a small volume fraction of very fine β laths at the interface between neighbouring α laths making a basketweave microstructure which is the normal microstructure produced by laser fabrication [11,12]. Fig. 4b shows the interface between the region at which the first increment of TiC was introduced and the 100%Ti6Al4V. The transition is basically smooth. The micrographs shown in Figs. 4c–i show the microstructures with increasing fractions of TiC, as indicated in Fig. 3. Thus Fig. 4c corresponds to a TiC feed rate of 0.14 g/min, Fig. 4d to 0.30 g/min through to Fig. 4i which corresponds to 100% TiC fed at 1.03 g/min. The volume fraction of TiC is obviously increasing along the sample height with eutectic carbide in Figs. 4c–f and increasing amounts of primary dendrites of TiC in Figs. 4c–i. Unmelted carbides are seen initially in Fig. 4f and are obvious in Figs. 4h,i. Thus for the conditions used here it appears that the maximum feed rate of TiC, which allowed all the TiC to be melted, was between 0.57 and 0.7 g/min. At higher magnifications some secondary carbides, formed by solid state precipitation can be seen as shown in Fig. 4j taken from the centre of the region where the feed rate of TiC was 0.44 g/min.

The volume fractions of TiC analysed by Zeiss KS 300 software within the seven regions indicated on Fig. 3, with microstructures shown in Fig. 4 are 8%, 15%, 24% 49%, 74%, 83% and 100%. The small volume fraction of secondary titanium carbide is not included in these figures.

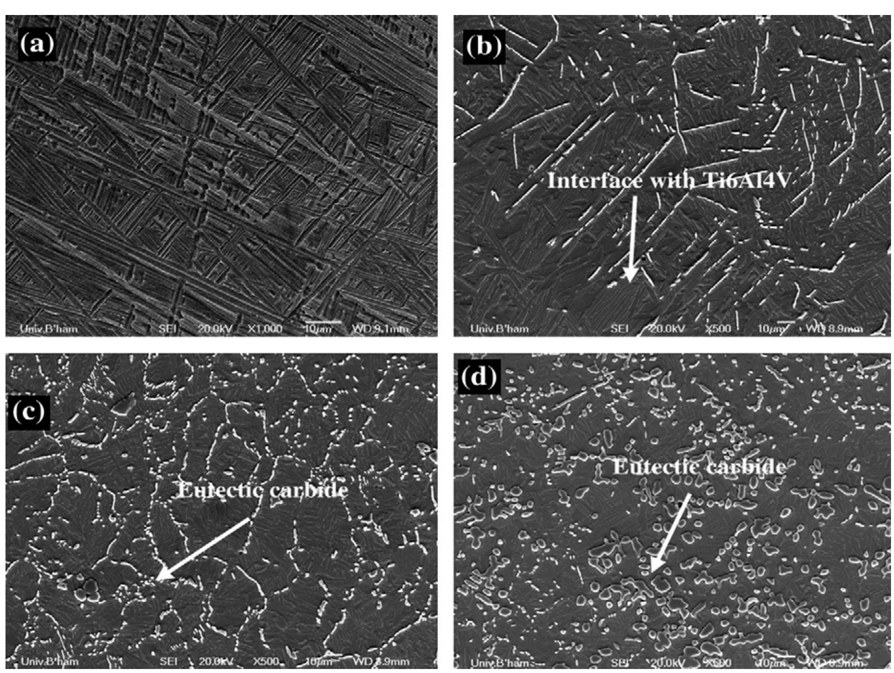

Fig. 4. Microstructure of compositionally graded Ti6Al4V–TiC made by direct laser fabrication using powder with a series of different feed rates and Ti6Al4V wire with a constant feed rate of 1.1 g/min: (a) Ti6Al4V wire feed only; (b) the interface between the composites and the Ti6Al4V; (c) TiC feed rate of 0.14 g/min, with 8% TiC particles in the microstructure; (d) 0.30 g/min, with 15% TiC particles; (e) of 0.44 g/min 24% TiC particles; (f) 0.57 g/min, with 49% TiC particles; (g) 0.70 g/min, 74% TiC particles; (h) 0.87 g/min, 83% TiC particles; (i) 1.03 g/min, 100% TiC particles; and (j) high magnification microstructure of the secondary titanium carbides taken from the centre of the region where the feed rate of TiC was 0.44 g/min.

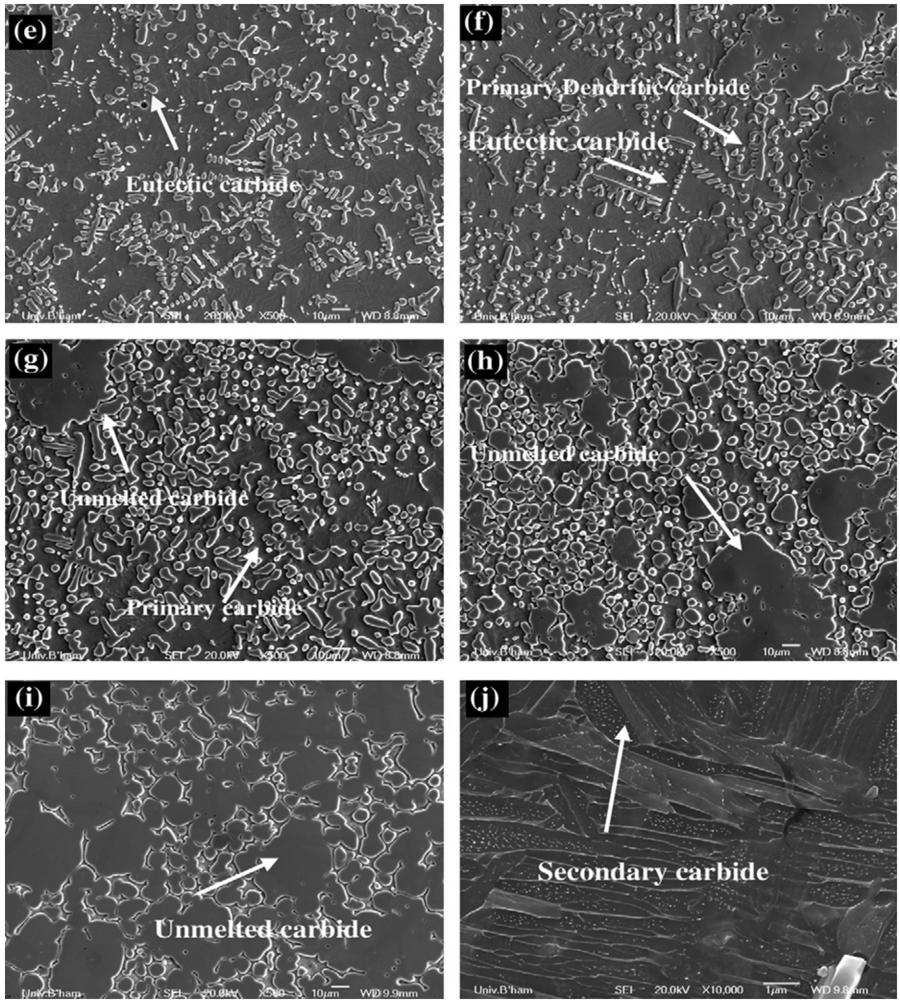

Fig. 4 (*continued*)

3.2. X-ray diffraction

Fig. 5 shows XRD data corresponding to different locations in the TiC-reinforced compositionally graded Ti samples. As expected the results show increasingly strong diffraction from TiC along the length of the build. Thus the results shown in Fig. 5a with Fig. 5b,c correspond to 0.14, 0.57 and 0.7 g/min TiC powder feed rate, respectively.

3.3. Tribological properties

Four different samples were selected for the preliminary pin-on-disc tests. They are 100% Ti6Al4V, Ti6Al4V with 8% volume fraction TiC which corresponds to TiC fed at 0.14 g/min; Ti6Al4V with 24% and 74% volume fraction TiC particles which corresponds to TiC fed at 0.44 and 0.70 g/min, respectively, as indicated in Fig. 3.

As expected, the 100% Ti6Al4V without TiC particles exhibited a very poor wear resistance as evidenced by the deep and wide wear track on the sample surface. Fig. 6

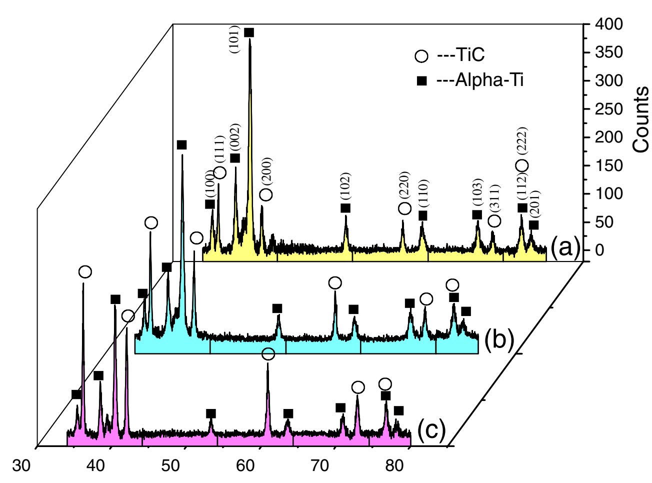

Fig. 5. XRD patterns obtained from different locations in the TiC-reinforced compositionally graded Ti alloys made by DLF: (a) corresponding to 0.14 g/min TiC powder feed rate, (b) corresponding to 0.44 g/min TiC powder feed rate and (c) corresponding to 0.70 g/min TiC powder feed rate.

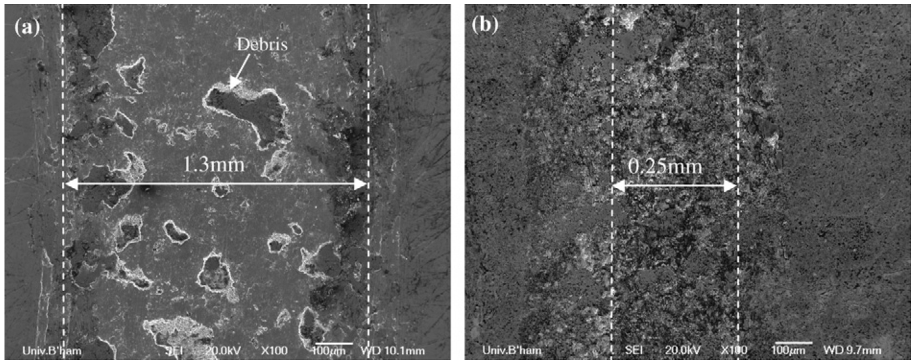

Fig. 6. Low magnification secondary electron scanning micrographs of the wear tracks on: (a) Ti6Al4V and (b) Ti6Al4V with 74% volume fraction of TiC particles. Sliding distance 250 m, contact load 10 N.

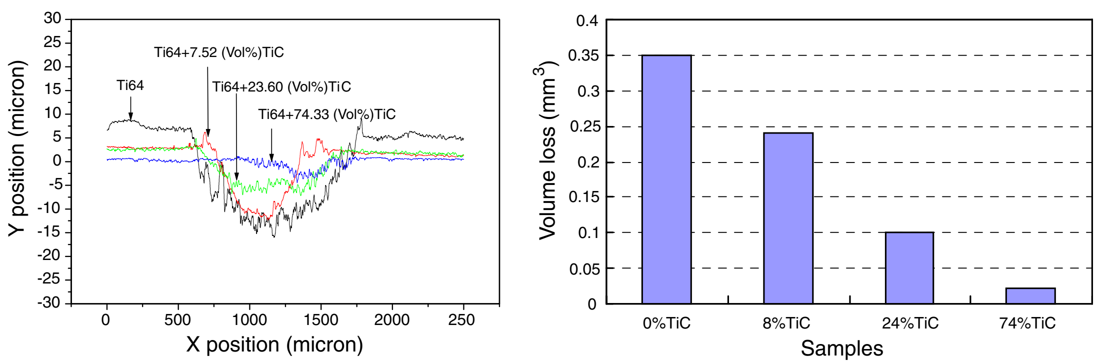

Fig. 7. Profiles across the wear tracks on the surfaces and the wear volume loss of Ti6A4V and Ti6Al4V with TiC particles after sliding for a distance of 250 m.

shows that the sliding distance of 250 m produced a wear track about 1.3 mm in width and 25 μm in depth on the Ti6Al4V. The wear tracks on the Ti6Al4V containing 74% volume fraction of TiC particles were found to be shallow and superficial, as shown in Fig. 6b.

Fig. 7 shows the profiles across the wear tracks on the surfaces of Ti6A4V and Ti6Al4V with TiC particles and the volume loss after sliding distance of 250 m. It can be seen that the tribological properties were dramatically improved by the TiC particles. The volume loss of sample with 74% volume fraction TiC-reinforced is only 0.021 mm^3, while the volume loss in the Ti6Al4V sample without TiC is 0.35 mm^3.

Close inspection of the wear tracks of Ti6Al4V and of Ti6Al4V with 74% volume fraction TiC showed that the wear mechanisms were different (Fig. 8). The wear on the Ti6Al4V occurred by a combined mechanism of adhesion, abrasion and plastic deformation. The debris of steel ball material and deformation area (Fig. 8), are all typical characteristics of adhesive wear.

With gradual increase of the TiC powder feed rate, the hardness of the Ti6Al4 was improved dramatically. This

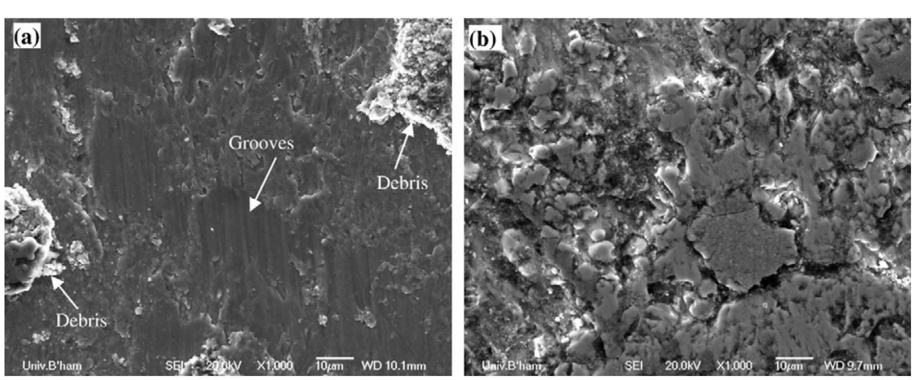

Fig. 8. Secondary electron SEM micrograph of wear tracks on: (a) Ti6Al4V melted by direct laser fabrication and (b) with 74% volume fraction TiC-reinforced composite sample. Sliding for 250 m, contact loads 10 N.

has essentially changed the wear mechanism as can be seen by comparing Ti6Al4V without TiC particles (Fig. 6a with Fig. 6b and Fig. 8a with Fig. 8b) which shows the wear track morphologies of Ti6Al4V with 74% volume fraction TiC. There are no obvious wear grooves on the surface of the sample containing TiC.

A close observation of the wear tracks (Fig. 8b) shows that there are some fractures on the surface of wear tracks. This indicates that the sample with 74% volume fraction TiC-reinforced is too brittle. A further longer distance (800 m) wear test shows that the wear tracks only became wider than 250 m wear test without any increase in depth, as shown in Fig. 9. The reason is that long distance wear test makes the steel ball surface more and more flat so that the contact area become larger and larger so that the wear tracks become wider but no deeper.

A study of wear test of Ti6Al4V with 24% volume fraction TiC particles sample shows that the wear mechanism lies between the two previously seen mechanisms. From Fig. 10a it can be seen that the size and the amount adhesion of steel ball debris are smaller and less than that of Ti6Al4V

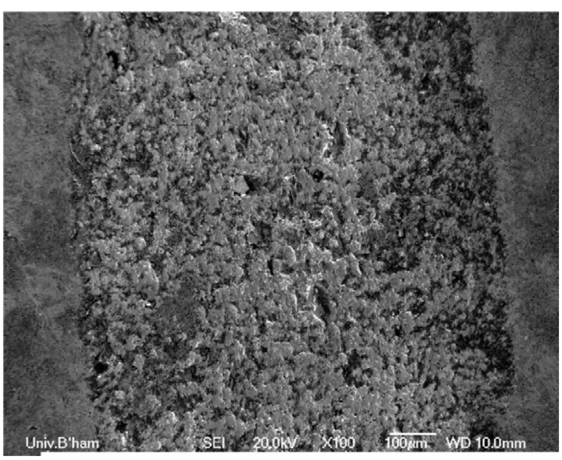

Fig. 9. Secondary electron SEM micrograph of the wear tracks on Ti6Al4V with 74% volume fraction TiC particles reinforced composite material. Sliding for 800 m, contact loads 10 N.

and there are no fractures on the surface of the wear tracks as shown in Fig. 10b. The comprehensive property of tribology and toughness of the sample containing 24 vol% TiC is the best among four of them.

4. Conclusion

(1) A compositionally graded TiC/Ti6Al4V material has been successfully fabricated by direct laser fabrication with TiC powder and Ti6Al4V wire fed simultaneously into the laser focal point.
(2) The TiC particles are distributed uniformly in the Ti6Al4V matrix, up to volume fractions of about 74% when unmelted TiC was observed.
(3) Preliminary sliding wear test shows that the Ti6Al4V tribological properties have been improved by the reinforced TiC particles, with the optimum balance of properties in the sample containing 24 vol% TiC.

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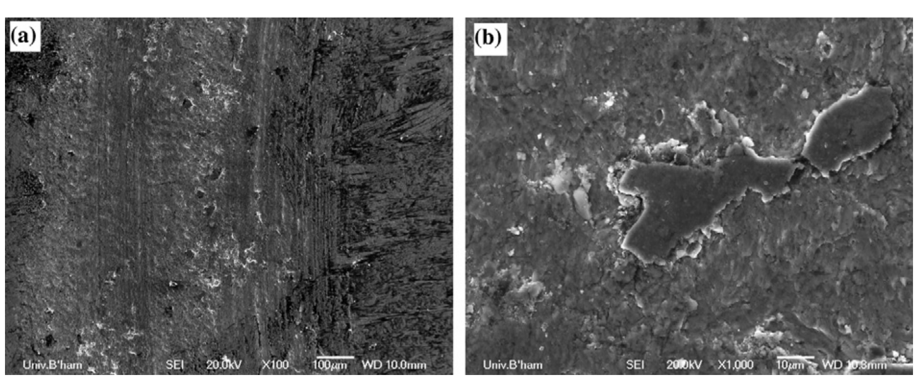

Fig. 10. Secondary electron SEM micrographs of the wear tracks on Ti6Al4V with 24% volume fraction TiC particles reinforced composite material: (a) low magnification and (b) high magnification. Sliding for 250 m, contact loads 10 N.

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